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Application of Acoustic Emission for Quality Evaluation of Fruits and Vegetables

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Additional information is available at the end of the chapter

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1. Introduction

Food crushing sound is one of the main factors used for food quality evaluation. Crispness and crunchiness are attributes of high quality product and are usually pointed on the top of a list of consumer preferences. However, the meanings of crispness and crunchiness are still imprecise. Its perception varies from country to country and from individual to individual. Despite of this there is a general consensus that crispy and crunchy sensation is related to fracture properties. Crispy product is mechanically brittle, firm and acoustically noisy as a result of large number of small fractures. Crunchiness is probably related to events (fractures) occurring on subsequent layers in a cell structure what gives the sense of extension of sound duration in time.

In spite of sensory and subjective nature of food quality evaluation by human senses, a big effort is put for objective sound properties analysis during biting and chewing and for developing instrumental methods for human independent food evaluation. The first instrumental analysis of sound was published by Drake in 1963, who found that crisper products emit louder sound and an average amplitude of successive bursts during mastication decreases [1]. Then, several authors used different sound descriptors for judging a chewing sound, as the number of sound burst in a bite n , the mean amplitude of the burst A or the products of these values nA or $nA/\text{sound duration}$ [1, 2, 3]. The first hypothesis was that the sense of crispness is an auditory phenomena, i.e. is the air-conducted sound. However, work done by Christensen and Vickers in 1981 showed that crispness may be a vibratory phenomena, i.e. is the bone-conducted sound [4].

Most of studies on crispness and crunchiness concern dry food products, like cakes, chips, etc.. However, this problem has been found as important also for fruits and vegetables called as wet food products. In 2002, presumably for the first time, Fillion and Kilcast stated

that crispness and crunchiness are very complex concept containing sound, fracture characteristic, density and geometry of fruit and vegetables [5]. They found that crispy wet food would refer to a light and thin texture producing a sharp clean break with a high-pitch sound mainly during the first bite with the front teeth. Crunchy wet food would be hard and has a dense texture producing loud, low-pitch sound that occurs over successive chews.

Many instrumental methods have been applied for crispness and crunchiness evaluation of fruits and vegetables. Due to the fact that mastication is a highly destructive process, mechanical tests are the most popular to simulate the biting. Results of such tests, like texture profile analysis, compression, tension, twist or three-point bending, show correlation with properties of a material thus can be also used for its texture evaluation. One of the simplest is a puncture test where probe is pushed into tissue and a maximum force is used as a firmness value.

As it was obtained by Christensen and Vickers [4] crispness may be by the bone-conducted phenomena. Therefore, the acoustic emission (AE) method where a sensor is in a contact with material investigated is promising tool for food properties evaluation. In general, the acoustic emission is monitored during deformation of a material to provide information on cracking and internal friction of material pieces by analysis of AE descriptors like: amplitude, frequency, energy, counts, events, etc..

2. Tissue model and source of AE in fruit and vegetables

The largest volume of fruit and vegetable tissue is taken by parenchymatous cells therefore this part of fruit is particularly often studied, also from the reason that it is relatively easy to cut a sample for testing. A simplified model of parenchyma tissue, which considers the most important mechanical actors, is shown in Fig. 1. The mechanical model is built of cells which are fluid filled and walls which are elastic-like. Cell walls are made of polysaccharides: cellulose fibrils network embedded in a matrix of pectins and hemicelluloses. Cells adhere to each other through middle lamellas which are made of amorphous pectins. Tissue structure also contains intercellular spaces, which for some fruits, like apple, can even take 25%. It is generally agreed that cell walls have elastic properties whereas pectins in the middle lamella are plastic-like. External forces which cause deformation of such structure increase a pressure inside the cells and tension in the cell walls. Simultaneously, shearing forces between cells increase. Thus, two failure modes are possible: cell wall rupturing and cell-cell debonding when strength of cell walls or/and intercellular adhesion is overcome, respectively. These two processes can be the sources of acoustic emission in the case of cellular plants. However, acoustic emission from cell-cell debonding due to plastic character is less likely compared to sudden rupturing of elastic cell walls.

Studying of cracking process of plant tissue is thus indeed important for understanding of quality of fruits and vegetables. When tissue cracks between cells, for example for fruit and veggie which have been stored too long, the material may show a mealy character whereas the fresh one, just after picking up, cracking through cell walls reveals juicy and crispy properties which are usually desired by consumers. Mechanical strength of plant tissue at micro-

structure level is also important not only from the point of view the sensory properties. For example, microcracking is important for blackspot bruising of potato which starts enzymatic browning of the tissue under the skin.

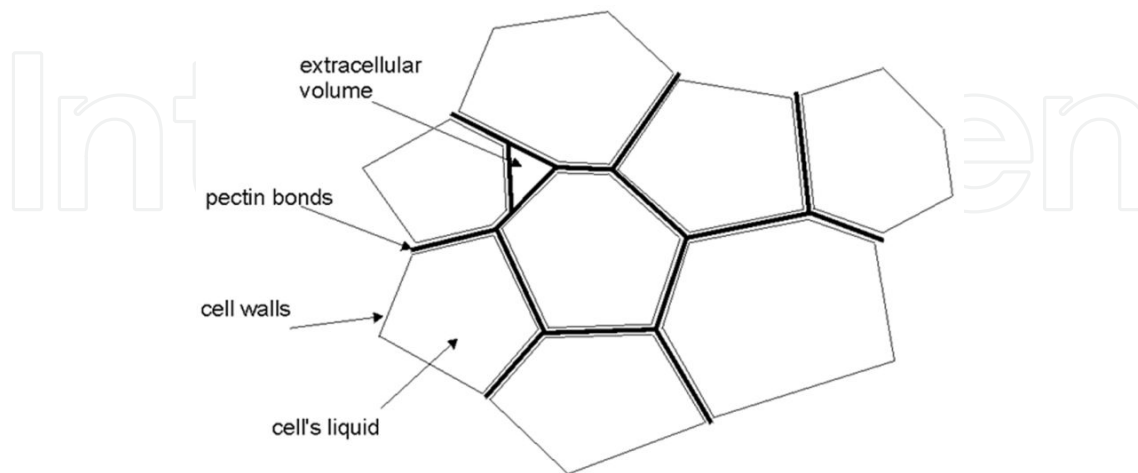


Figure 1. A simplified mechanical model of parenchyma tissue of fruits and vegetables

3. Acoustic emission (AE) for evaluation of the onset of plant tissue cracking

As it is for other solid materials, acoustic emission has been found as a very useful method for monitoring of cracking of plant tissue under external loading. AE has been applied for this group of materials for the first time in the late 90's [6]. The first attempt was aimed on observation of the AE signal from damaged sample of potato tissue. Figure 2 presents scheme of the first apparatus used. A one-column and low noise testing machine was used for studying the mechanical properties and forces that participate in the process of plant tissue cracking. In that work a wide-band piezoelectric sensor was used for the recording of the acoustic emission signal with high-sensitivity in the frequency range from 25 kHz to 1 MHz. Due to a small size of the samples which are usually used in experiments with plants and relatively large deformations which can cause friction between sensor and sample, fixing the AE sensor directly on the sample was impossible. This problem was solved by fixing the sensor to the jaw of the testing machine, like it is shown in the Fig. 2. Since the AE signal passes from the material with lower density and enters into the material with higher density at the border between the sample and the jaw (sample of tissue – steel), sensitivity of measurement is sufficient to record even small AE events. In order to eliminate any friction and improvement of sound conductivity, silicon grease was applied on each boundary on the way of elastic waves from sample to sensor. A set consisted of a pre-amplifier (40dB) with a high-pass filter (25 kHz) and a low-noise amplifier with adjustable gain was used for signal conditioning. The set was supplemented with a high speed transducer card A/D that al-

lowed for the recording of counts, events and energy in time intervals from 0.001 to 1 second or fast sampling with 2.5MHz short samples 0.25 s long.

The most useful method of analysis of AE signal bases on the transformation of the time signals to the form of descriptors recorded in time intervals. If a certain threshold is established for the amplitude of the received signal, called a discrimination threshold, then every time the amplitude goes above this signal is recorded as one count. Groups of the AE signal with the characteristics shape of a damped sinusoid curve are called events (Fig. 3). Instead of analysis the shape of event, it is possible to define an AE event as a group of counts recorded in consecutive samples. The number of counts and the number of events recorded in time gates are called count rate and event rate. Registered AE signal, presented in Fig. 3 in amplitude – time coordinates can be also characterized by AE energy E . Assuming that a signal event of duration t and of peak amplitude V of an event, then energy of each event can be evaluated as:

$$E = 0.5V^2t \quad (1)$$

Besides the parameters mentioned above, other parameters based on the transformations of time or spectrum of the AE signal could be also used. Detailed definitions and descriptions of the AE signal descriptors can be found in literature [7]. The system presented in Fig. 2 also allowed for simultaneous measuring mechanical and acoustical properties. For example, stress and AE counts as a function of strain could be recorded together as it is shown in Fig. 4.

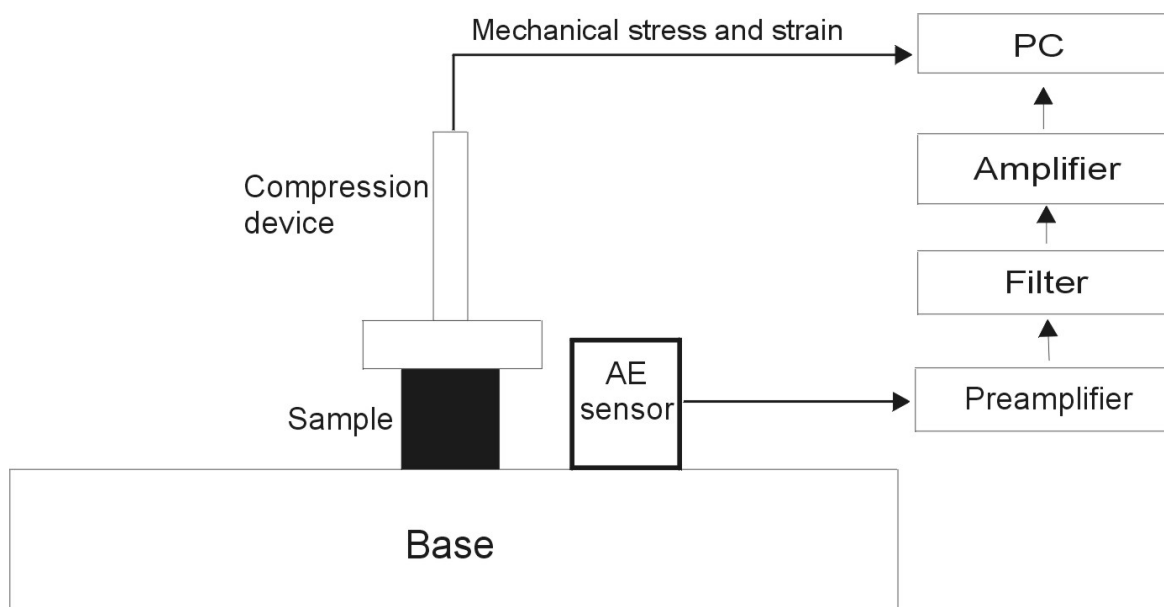


Figure 2. Scheme of the first apparatus used for acoustic emission recording from deformed plant tissue (based on the work of Zdunek and Konstankiewicz [6]). The EA 100 was the analyser which allowed both recording samples with 2.5MHz and conversion of the signal to AE descriptors

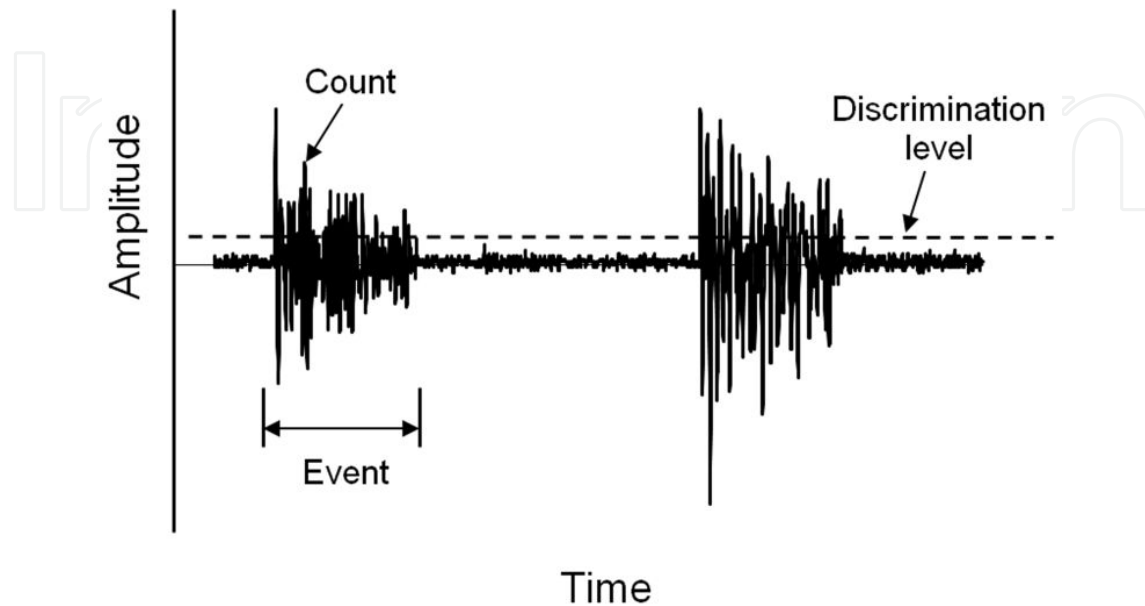


Figure 3. The method of determination of AE descriptors: counts and events from time-amplitude signal. The discrimination level is found experimentally to avoid external noises, for example from the loading device

In Fig. 4 it is easy to notice that for a decrease in the slope of the stress-strain curve (bioyield and rupture points in this case), a high value of AE counts was observed. The highest values, however, appear at the moment of sudden rupture. Macro-cracks of the samples are clearly visible on the cross-sections of the sample after rupture, and sometimes are even audible to human ears. Before rupture, presumably some cracks also appear, particularly in the region close to bioyield, however it is difficult to detect them visually. The acoustic emission signal shown in Fig. 4 unambiguously proves that bioyield point and rupture could be assigned to tissue cracking, however maybe at different scales. Moreover, a long before bioyield, AE signal has been detected too, although with significantly lower number of counts. In this region of deformation no noticeable decrease in the slope of the stress-strain curve was observed. Generally, the AE counts before bioyield is more irregular and have lower values in comparison to acoustic signal after bioyield point. It is believed that microcracking is developing gradually due to heterogeneous structure of the plant tissue even before it could be noted from force-deformation curve. This is particularly important because even a small crack of tissue, for example damage of intercellular plasmalemma, could start irreversible biochemical processes which decay quality of the material or affect its function.

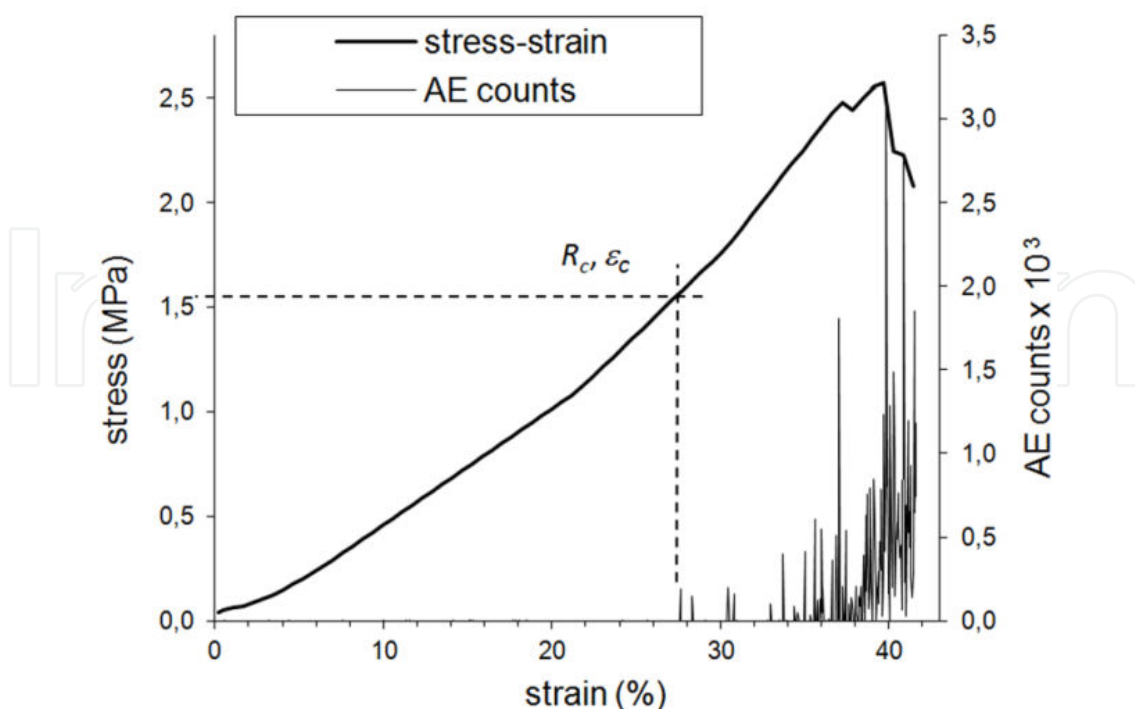


Figure 4. Examples of simultaneous recording of stress, strain and AE counts for potato tuber tissue. Bioryield point is visible as the short drop down of the stress-strain curve, rupture is visible as major final fall down of the stress, and the critical point as the onset of the acoustic signal (AE counts). The critical stress (R_c) and critical strain (ϵ_c) define the critical point (result obtained by the author)

In the first paper on application of AE for potato tissue, new mechanical parameters have been proposed. Critical stress (R_c) and critical strain (ϵ_c) have been defined as the mechanical conditions at the onset of acoustic emission. In further studies critical stress and critical strain was analysed under different conditions of mechanical test (Fig. 5) and samples itself (Fig. 6).

Fig. 5 presents how the critical stress and critical strain change with strain rate of two potato cultivars (*Solanum tuberosum* cv. Danusia and Kuba). An increase in the strain rate decreases exponentially both parameters. From microscopic point of view, deformation of plant tissue causes changes in the cell shape. Since initially cells of parenchyma tend to have rounded shape due to incompressibility of the intracellular fluid, the ratio of cells surface to cells volume increases. This means that cell walls are generally stretched during deformation. The tension force in the walls is a function of strain rate and wall permeability. In a simplified model, low strain rate has an effect similar to that of high permeability in the model. At a relatively high strain rate, a seepage of the intracellular fluid through the walls is limited and leads to a higher tensions at the same cell deformation. When the strain rate is low, the intracellular fluid has relatively more time to flow out of the cells, and this produces smaller increases of the tensile forces in the walls. Thus, in this case the strength limit of the cell wall can be reached at higher cell deformation and higher external forces. For relatively slow cell deformation, the cell can even be completely compressed without wall rupture. This explains the pronounced increase of the critical values at very slow rates (Fig. 5).

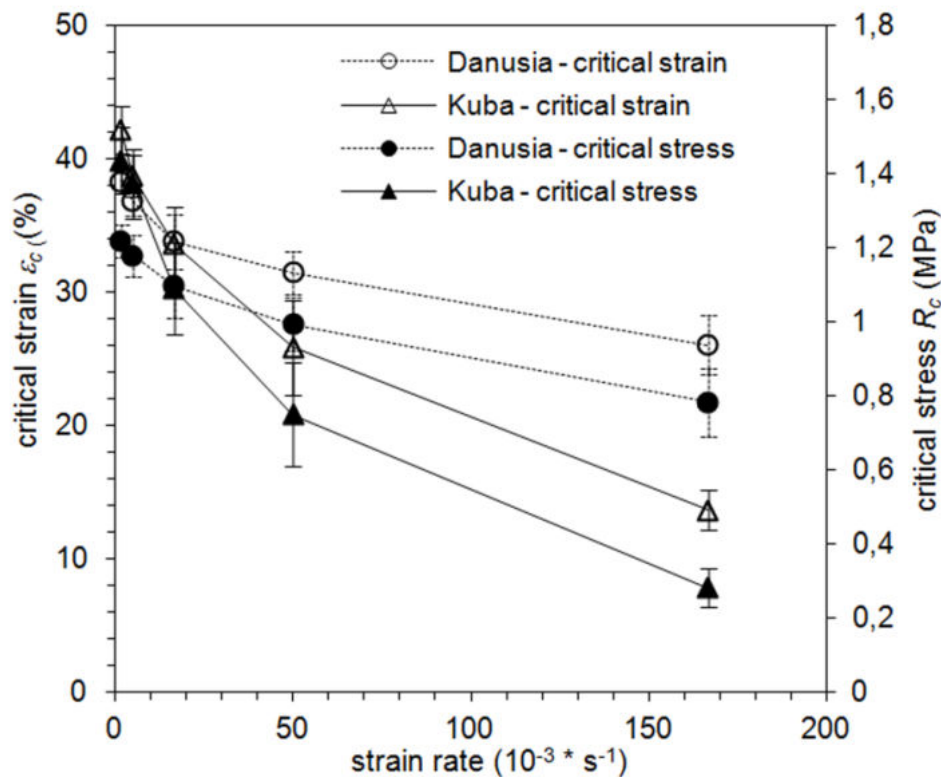


Figure 5. Critical stress and critical strain obtained as the onset of AE during compression of two potato cultivars 'Danusia' and 'Kuba' with different strain rates (result obtained by the author)

The relations between critical stress, critical strain, and osmolality of mannitol solutions in which the samples were hydrated or dehydrated are shown in Fig. 6. Higher osmolality of the mannitol solutions corresponds with lower turgor of the tissue reached after 24h treatment. A strong influence of tissue turgor on critical stress and failure stress was observed. Both critical stress and failure stress increase in a linear manner when turgor decrease (direction of turgor change is shown in Fig. 6). The turgor effect can be interpreted in terms of a model of a single cell. Before deformation, higher turgor causes larger preliminary tension in the cell wall. Thus, the additional cell deformation or the additional external force necessary for wall rupture are lower.

Application of the acoustic emission method has proven that micro-cracking of tissue starts significantly earlier than it can be observed on the stress-strain curve. However, no correlation between the critical values and the failure values of samples tested under the same conditions (the same strain rate or turgor) has been observed [8]. This means that observation of the critical values does not allow prediction of the bioyielding conditions for example. This is presumably result of the fact that critical point and the bioyield point are different stages of cracking. Between them cracking is developing, from the first local micro-cracks to large macro-cracks. This propagation may be very chaotic and accidental due to heterogeneous microstructure of a tissue.

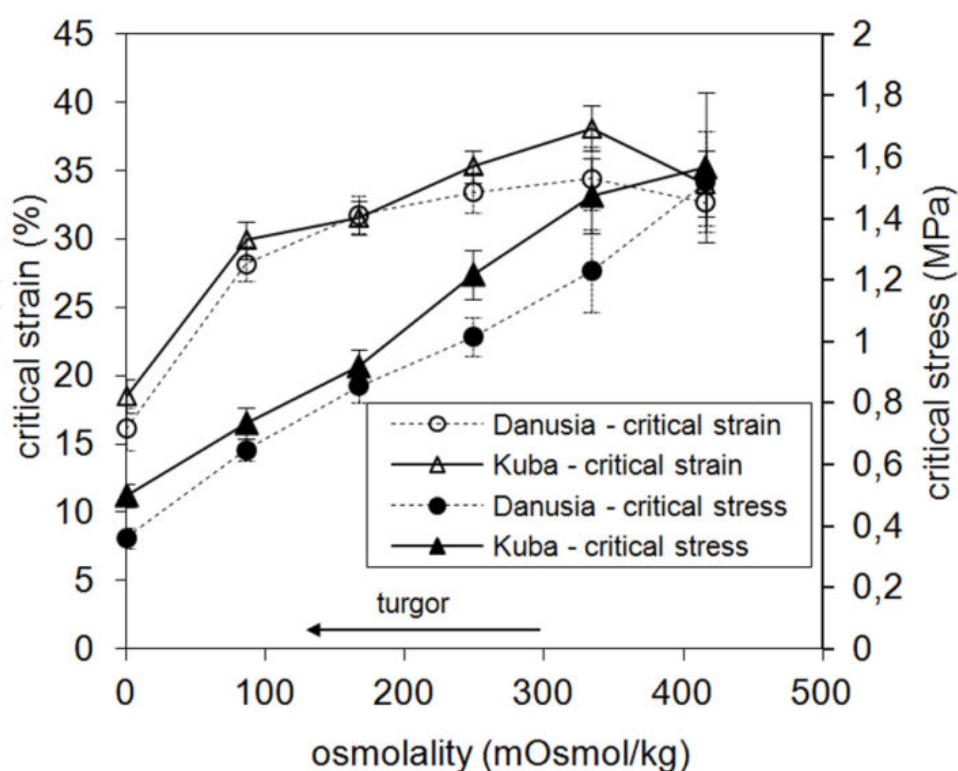


Figure 6. Critical stress and critical strain obtained as the onset of AE during compression of two potato cultivars 'Danusia' and 'Kuba' dehydrated and hydrated in different mannitol solutions (result obtained by the author)

4. Acoustic emission and different mechanical tests

4.1. Puncture test

Application of acoustic emission is possible in any mechanical test which are used commonly for plants. The key issue is to apply AE sensor to the sample which in the case of plants is usually largely deformable. Solution presented previously uses indirect attachment through solid body. This solution was proven to be very effective in various mechanical tests. Sensors of AE could be placed inside device for mechanical tests, exactly in the probe for material deformation. Such device for puncture test is presented in Fig. 7. Here, acoustic emission during the puncture test is caused and recorded by head with two sensors placed inside. The head consists two parts. Top part is made of ertacetal and the bottom part is made of duraluminium which effectively conducts elastic waves. The application of two different material was intended to limit eventual disturbances from mechanical system. They are screwed to each other. Acoustic emission sensors are glued (or it can be screwed also) to the top surface of the metal part. In the system presented in Fig. 7, one sensor works in audible range 1-16kHz (SA), whereas the second sensor has maximum sensitivity in ultrasound range 25-100kHz (SU) to cover as wide as possible frequency region. The sensors are connected to individual amplifiers with adjustable amplifying. The signal is filtered in the range

1 kHz -20 kHz for lower band and 10kHz-900 kHz for higher band. Next, the analogue signals are converted into digital one by A/D boards. Sampling rates per channel: 44 000 and 150 000 samples per second are more than double of the frequency range of the sensors used. The second channel of each card is used for recording an analogue signal of force delivered from universal testing machine to synchronize both acoustic and mechanical signals.

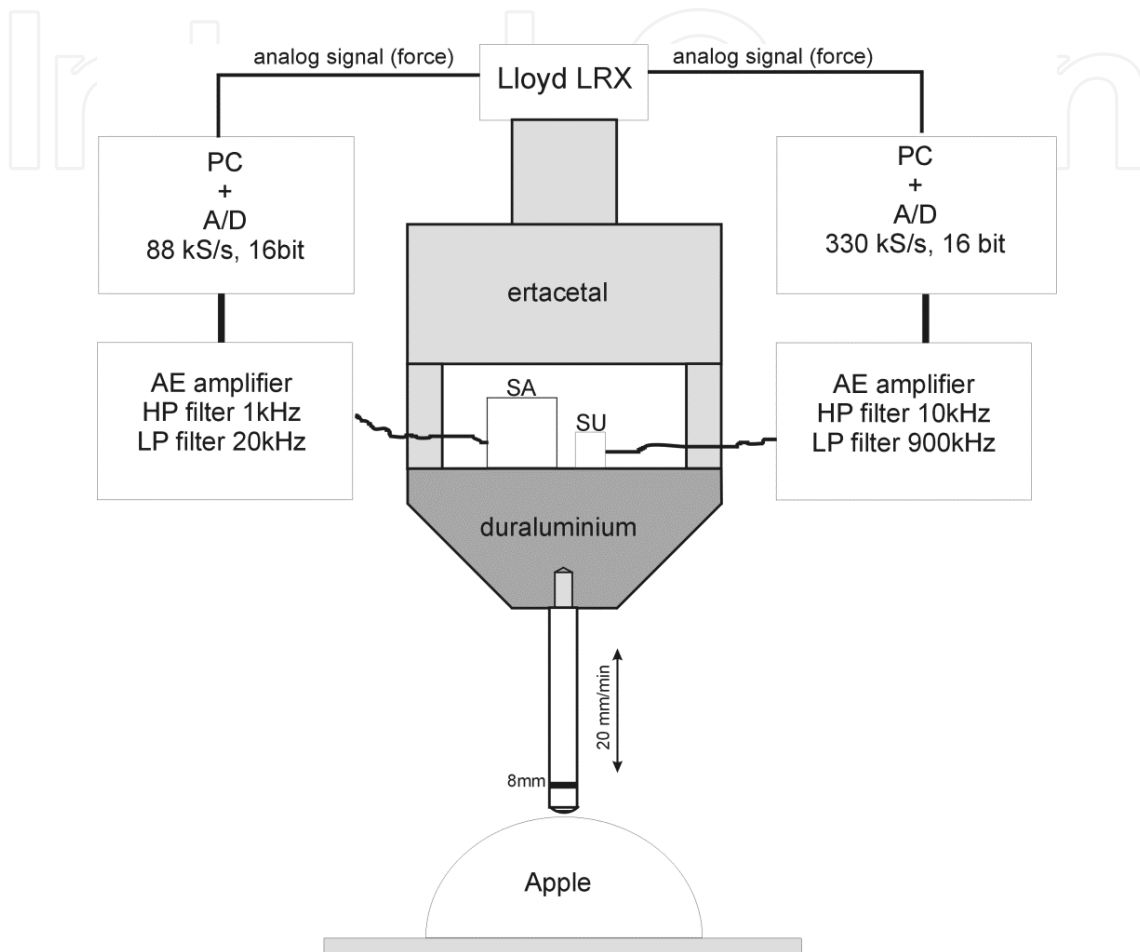


Figure 7. Scheme of the system for recording of acoustic emission from punctured fruit. Two channels were used: 1-16kHz and 20-75 kHz. Puncturing was performed with Lloyd LRX device. SA is the sensor for audible frequencies, SU is the sensor for ultrasound frequencies. Dimensions of the puncture probe are exemplary (scheme by the author)

In Fig. 8, typical profiles of acoustic emission counts recorded during puncturing of apple flesh are shown. In the case of apple puncturing, the AE signal starts just from the moments of touching puncture probe to tissue. The number of counts increases progressively up to a moment when force-deformation curve yields. At this moment the whole curved part of the probe is in a contact with the tissue. When the probe goes deeper into apple tissue the acoustic activity decreases. This could be result of damping of acoustic waves by surrounding tissue and already damaged tissue layers under the probe. In many studies, softening of apples during ripening and storage has been reflected in a lower penetration force (lowering firmness). The integrative use of contact AE and the puncture test showed that major acoustic signals are observed together with drops of force. The coincidence was interpreted as an

energy release in the form of sound as a result of material fracturing. In the case of plant tissues, AE signal comes mainly from rupture of the cell wall because of its somewhat elastic properties, whereas the middle lamella due to plastic properties rather do not generate sound. This hypothesis is supported by analysis of AE during ripening of apples, which will be discussed later on in this chapter.

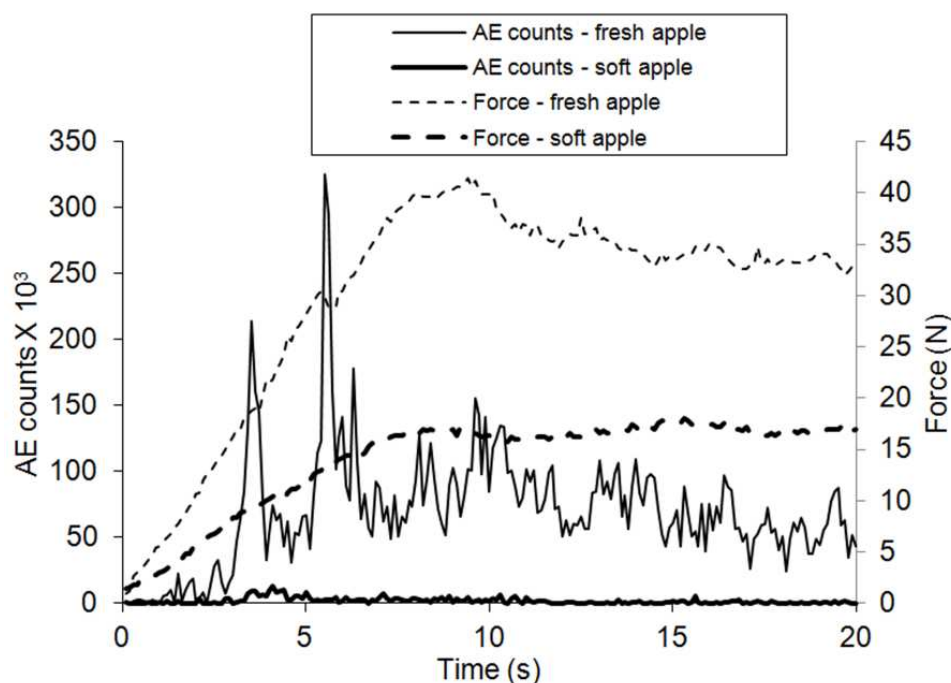


Figure 8. AE counts and force recorded during puncturing of fresh (1 day of shelf life) and stored (10 days of shelf life) apples (result obtained by the author)

In Fig. 9, spectrum of the signal is presented from two frequency ranges in a form of “acustograms”. Colors in the acustograms represent a power of the signal in time-frequency coordinates. A few dominant frequencies can be found: 5.5 kHz, 9.5 kHz, 15 kHz, 32 kHz, 44 kHz and 56 kHz. They constantly appear during puncturing. Precise analysis showed that they are also characteristic for the system used because no significant changes were found with properties material used. The only one change observed with change of properties of the material was an overall change in amplitude that occurred uniformly for all bands. Additionally, Fig. 10 presents relation between AE energy in 1-16 kHz and 20-75 kHz obtained for a large set of apples in puncture test. It is shown that the relation is very linear and in the case of this material, investigation in higher band does not provide any additional information.

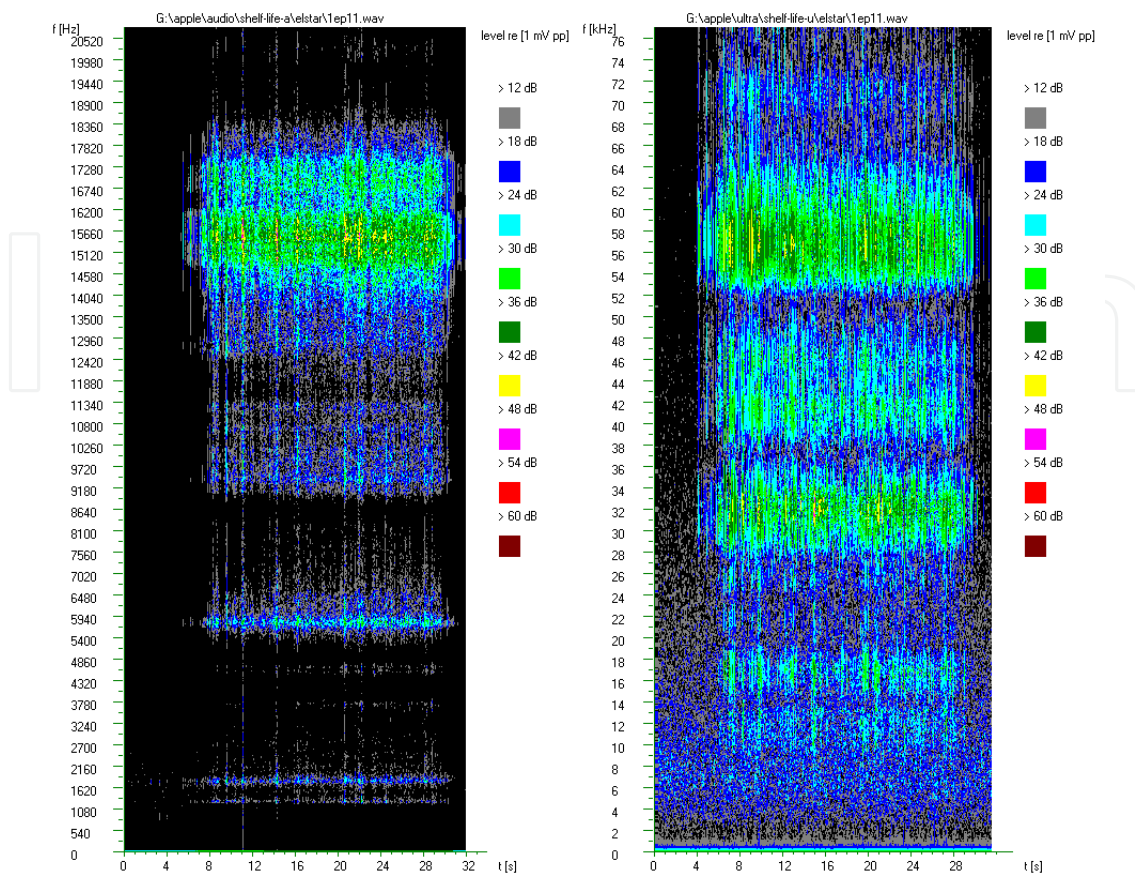


Figure 9. Acoustograms of apple tissue in puncture test within frequency range 1-16 kHz (left) and 20-75 kHz (right), f – frequency, t – time (result obtained by the author)

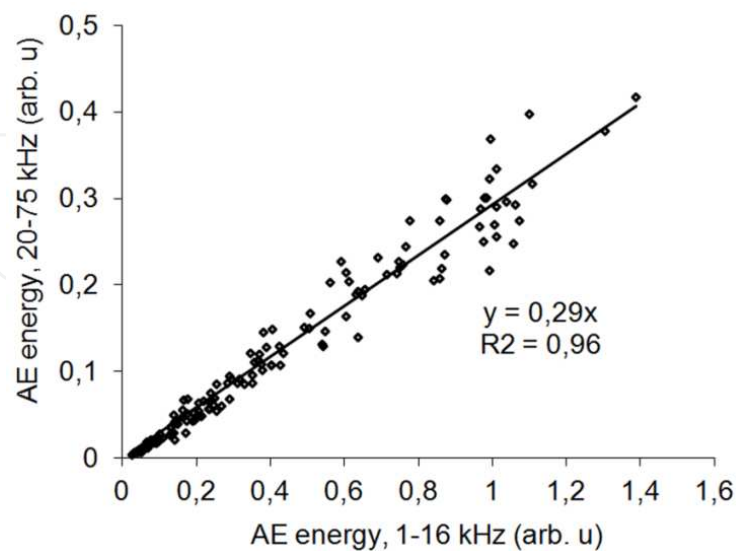


Figure 10. Relationship between the total energy of acoustic signal recorded within frequency range 1-16 kHz and 20-75kHz for apples in puncture test (result obtained by the author)

Fig. 11 presents changes of total AE events and mean AE amplitude during shelf life storage of three apple cultivars. Data was obtained in puncture test. AE descriptors decrease almost linearly during shelf-life storage revealing large Pearson’s correlation coefficients R with time of storage (Table 1). In Fig. 11 is visible that the acoustic emission method is very sensitive for registering changes that occur during postharvest storage of apples. Total number of AE events and mean AE amplitude usually shows higher R value when compared to firmness from puncture test (Table 1).

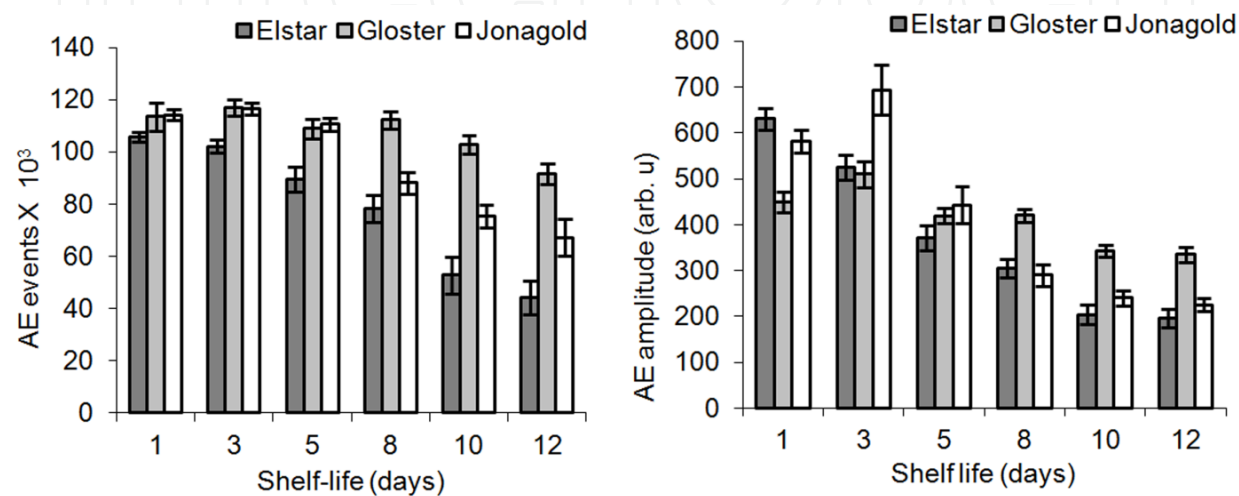


Figure 11. Total number of AE events and mean AE amplitude registered in puncture test of apples (three cultivars) during shelf life storage (result obtained by the author)

Variable	R		
	Elstar	Gloster	Jonagold
AE events	-0,80	-0,54	-0,81
AE amplitude	-0,90	-0,70	-0,88
Firmness	-0,80	-0,40	-0,82

Table 1. Correlation coefficients R of changes of AE events, AE mean amplitude and firmness, in puncture test of apples with shelf-life days for three cultivars ‘Elstar’, ‘Gloster’ and ‘Jonagold’ (results obtained by the author)

The postharvest softening of apples is caused by biochemical processes. During apple ripening two major processes occur that affect the mechanical properties of the tissue including its fracturing mechanism. Pectin degradation during ripening causes a decrease of adhesion between cells leading to tissue softening and changes the fracturing mode toward cell–cell debonding. As a result of respiration and metabolism during storage, turgor pressure can decrease, which has consequences for the fracturing process. The lower tension of the cell wall at low turgor causes a greater deformation that leads to wall fracture. Another consequence of low turgor is a decrease of cell–cell adhesion. Thus, in general, degradation of

pectins and lower turgor lead to changes of fracturing mode toward cell–cell debonding. Due to the microstructure, the thin cell wall in plants is considered as an elasto-plastic material. The elasto-plastic character of the cell wall is responsible for the brittle fracturing necessary for sound generation. The intercellular lamella between cells consists of amorphous pectin and are considered as plastic. It is probable that the pectin plasticity causes slow dissipation of strain energy and no brittle fracturing without sound generation. Therefore, it is most likely that the sound made during puncturing is generated mostly when cell walls fracture. In material science terms, a crack propagates if there is a stress concentration into a small tip zone. Thus, propagation is ineffective if there is any plastic zone (in the case of apples it would be pectin). Other features that halt crack propagation are the cell interiors or intercellular spaces. There is ~ 25 % space within apple tissue, and this amount increases with ripening. Thus, ripening attenuates conditions of cracking propagation. Again, in terms of material science, the cell wall (as the material where the stress can concentrate) has a key role in crack propagation.

The maximum number of acoustic events recorded after pushing the probe into the apple flesh was about 10^5 (Fig. 11), which was obtained for fresh apples immediately after harvest. This number agrees roughly with the number of fractured cell walls during the test estimated on the basis of two assumptions; that the mean cell diameter is ~0.25 mm, which is true for apples, and all cells in the path of the probe are damaged (i.e., all cell walls are broken). This result shows that the breakage of each cell wall would be the source of single acoustic event. The mean AE amplitude depends on a stress value in the source of cracking (i.e. the strength of the cell wall) and on the attenuation of the elastic waves on the way from the source to the sensor. As mentioned above, pectin degradation occurs during apple storage, which can decrease the strength of the cell walls due to an increased mobility of cellulose fibrils in the pectin matrix. On the other hand, softening of the bulk tissue caused by pectin degradation in general and the decrease of turgor, increases the attenuation of the elastic waves. Both causes that amplitude decrease with softening of apples.

4.2. Texture Profile Analysis (TPA)

Texture profile analysis (TPA) is used for simulation of eating process. Compression test is performed in two cycles to the same deformation level of a sample. Scheme of TPA test and graphical representation of TPA descriptors used for sample characterization are shown in Fig. 12. Texture profile analysis is performed on cylindrical samples in two cycles. Maximum deformation applied could be about 20-40% of initial sample height for both cycles, depending on sample strength (20% for apple, 40% for potato). Maximum deformation 1 should be close to failure points of investigated material. TPA requires cracking of the test material to simulate the destructive process during eating. On the other hand, deformation should not be too far to prevent the compression of the small pieces of the initial sample in the second cycle which causes springiness and cohesiveness to become physically meaningless. The probe always returns to the trigger point after the first cycle. No rest periods is programmed between the TPA compression cycles to avoid material relaxation. The textural parameters are calculated in the following way (Fig. 12). Hardness 1 is the force peak of the

first cycle. Hardness 2 is the force peak of the second cycle. Cohesiveness is calculated as the ratio of the area under the curve of the second cycle to the area under the curve of the first cycle. Springiness is the ratio $L2/L1$, where $L2$ is the time or distance from the beginning of the second cycle to hardness 2 point and $L1$ is the time or distance from the beginning of the test to the hardness 1 point. Acoustic emission during the TPA could be recorded using the same head as for the puncture test described above.

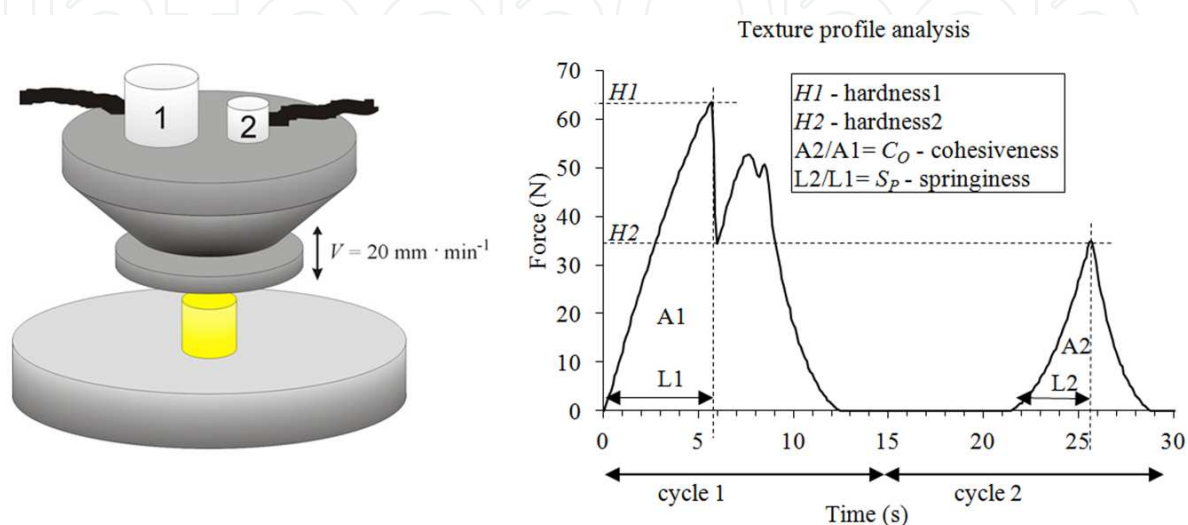


Figure 12. Scheme of TPA test performed on cylindrical sample of plant tissue. Proposed positioning of the AE sensors (1 and 2 with different frequency range) is shown. The upper plate for compression is removable to change a probe for other mechanical tests. Graph to the right presents typical TPA curve with the method of calculation texture descriptors (by the author)

Typical TPA curves together with acoustic emission counts for apple and potato are shown in Fig.13. For comparison, results for two apples, fresh and soft one are plotted, and for hydrated potato sample. The fresh tissue has higher hardness 1 which was reached earlier than in the case of the soft tissue. The range of macro-cracking, visible as the gradual force decrease in the first cycle, is longer and more jagged. The second cycle of TPA also shows larger forces in comparison to soft sample. It is typical that for fresher samples and with higher turgor, the failure occurs at a lower deformation or earlier on the time axis. Acoustic signal appears earlier and it has higher values in the case of fresh apple than in the case of soft one. In apple, acoustic counts are recorded almost from the beginning of the compression. This would be a result of both weaker cell walls and intercellular bonds than for potato which is actually very dense and strong tissue. Failure is accompanied by high acoustic emission counts for both materials as a result of macro-cracking (Fig. 13). This moment is also usually air-conducted and audible. The acoustic emission in TPA is recorded mainly during the downward movement of the machine probe. During the upward movement, a small signal is only observed just after the probe starts returning. It disappears at the end of the returning stage. The second cycle of TPA may also cause acoustic emission. However, the signal is usually weak especially in the case of apple. The second cycle in TPA starts from the trigger point of the first cycle. Thus, the time of deformation during the second cycle is related to

recovery of the material after the first cycle. If a crack occurs during the first cycle, it can propagate during the second one. If the material failed during the first cycle (macro-cracking occurred) relaxation of the material is less and deformation in the second cycle is also smaller. Therefore cracking propagation is less and, as consequence, acoustic emission is low. In other words, the weakening of the material in the first cycle causes only small acoustic emission due to the propagation of already existing cracks within the material during the second cycle.

Fig. 14 and Table 2 show decrease of acoustic descriptors during shelf life and that the correlation with days of storage is in general similar as for mechanical descriptors from this test.

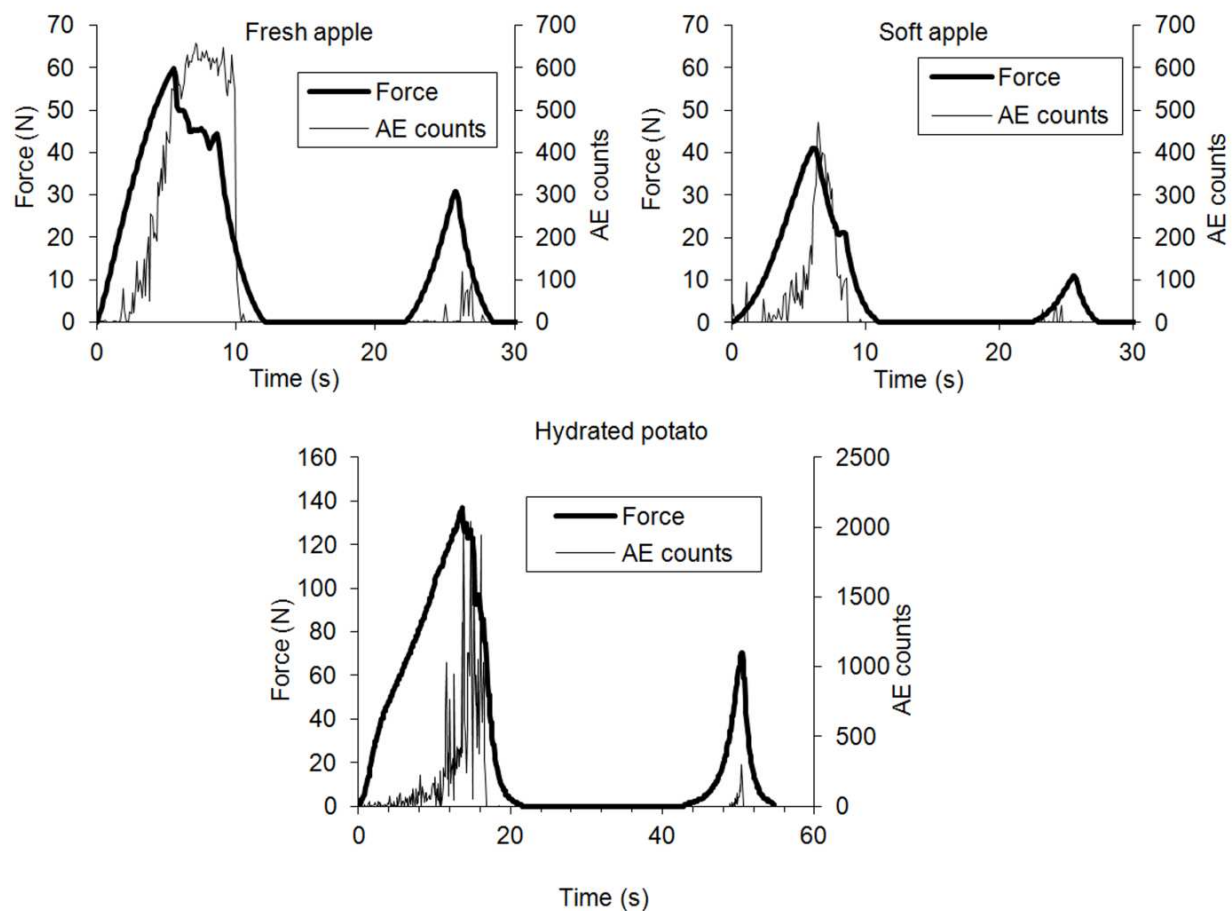


Figure 13. Typical TPA curves with AE counts for fresh and soft apple, and for hydrated potato sample (result obtained by the author)

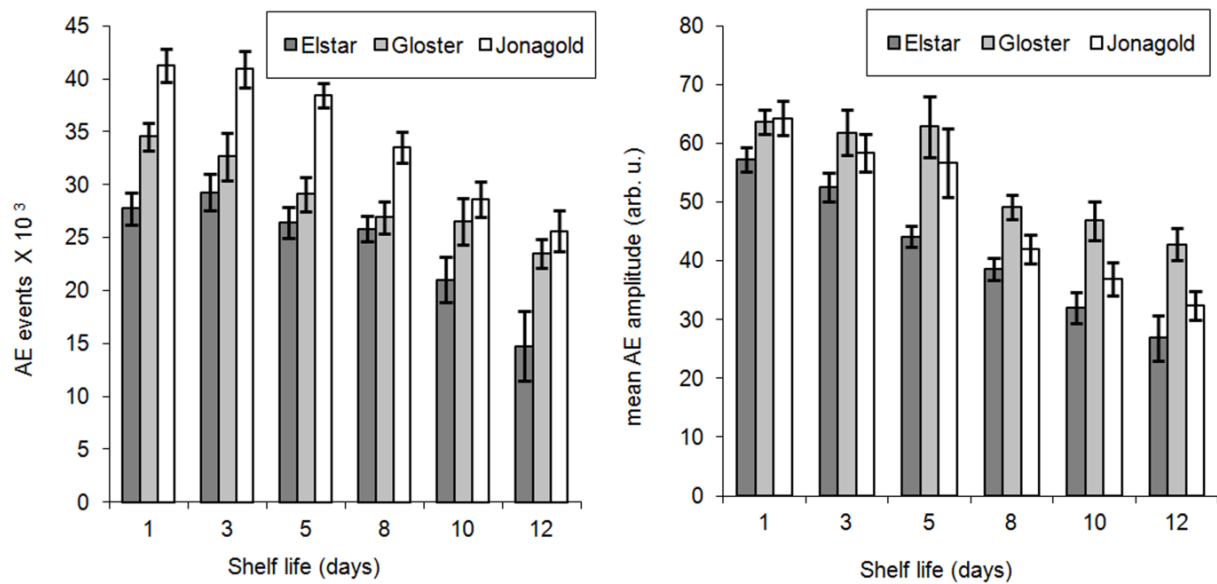


Figure 14. Change of acoustic descriptors obtained in TPA test during shelf life storage for three apple cultivars (result obtained by the author)

Variable	R		
	Elstar	Gloster	Jonagold
AE events	-0,58	-0,64	-0,78
Mean AE amplitude	-0,83	-0,70	-0,82
H1	-0,78	-0,19	-0,85
H2	-0,78	-0,33	-0,83
C _o	-0,45	-0,19	-0,44
S _p	-0,23	0,27	0,38

Table 2. Correlation coefficients between AE events, mean AE amplitude, hardness H1 and H2, cohesiveness C_o, springiness S_p in TPA test and shelf life days for three apple cultivars ‘Elstar’, Gloster’ and ‘Jonagold’ (result obtained by the author)

4.3. Single edge notched bending (SENB)

Recently, new engineering mechanical tests has been introduced for analysing the fracture properties of plant tissue, so called single edge notched bending (SENB) [9]. In the test rectangular sample with a notch is bended to breaking up. From sample geometry and from failure force obtained from force-bending curve, a critical stress intensity factor K_c can be calculated. This material parameter is tried to correlate with textural properties of a tissue, like crispness or crunchiness. However, from mechanical point of view, the critical stress intensity factor is a force criterion for starting cracking propagation up within material.

Single edge notched bending is performed on rectangular beams according to the ASTM Specification E-399 standard. It is very often that fruit or veggies size or geometry does not

allow cutting desired by the standard sample dimensions, which should be also sufficient to produce detectable acoustic emission. According to the standard, $S/W=4$ (span/height) is suggested [10]. Sample of potato tissue of height $W=16$ mm and width $B=8$ mm emits strong enough signal in the system showed in Fig. 7 and Fig. 15. Although, to keep the ratio the span should be 64mm, it is usually difficult to cut samples longer than $L=40$ mm from typical potato or apple.. Therefore, the span most often must be shortened to $S=32$ mm for example, which is reasonable and gives $S/W=2$ ratio. According to standard, in the middle of the sample a notch with depth of $a=8$ mm is cut.

Scheme of SENB test configuration is presented in Fig. 15. Acoustic emission during the SENB could be recorded using the same head as for the puncture test described above where one or more AE sensors could be placed. Sample is placed on support with the notch to the bottom. Bending is performed up to fracture of the sample.

SENB allows determination of a critical stress intensity factor K_c . The K_c can be obtained using formula:

$$K_c = \frac{P_c S}{B W^{\frac{3}{2}}} f\left(\frac{a}{W}\right). \quad (2)$$

where: S - span, P_c is a failure force. Function $f(a/W)$ is given as:

$$f\left(\frac{a}{W}\right) = \frac{3A\left(\frac{a}{W}\right)^{1/2}}{2\left(1 + \frac{2a}{W}\right)\left(1 - \frac{a}{W}\right)^{3/2}}. \quad (3)$$

where:

$$A = 1.99 - a/W \left(1 - \frac{a}{W}\right) \left(2.15 - \frac{3.93a}{W} + \frac{2.7a^2}{W^2}\right). \quad (4)$$

K_c has a physical meaning if following formula is true:

$$B_c \geq 2.5 \left(\frac{K_c}{\sigma_y}\right)^2. \quad (5)$$

where: B_c is minimal width of a sample used, σ_y is a failure stress in uniaxial compression of the same material.

Figure 16 presents typical SENB curve and acoustic emission events for fresh and soft apple. AE signal starts just from the beginning of bending which suggest that cracking propagation also starts from the tip of the notch. For fresh apples, which is also harder and has higher K_c value, AE is significantly larger than for the soft material however in both cases acoustic emission lasts up to sample fracture.

SENB test, similar to puncture and TPA, is able to distinguish sample according to its softness. Fig. 17 presents example for three apple cultivars which were stored at shelf life conditions. It is visible that acoustic descriptors diminishes during storage. Table 3 presents correlation coefficients of parameters obtained from SENB test with time of shelf life storage. The coefficients for acoustic descriptors are higher than these for mechanical descriptors which shows again that AE method is very suitable for monitoring properties of fruits.

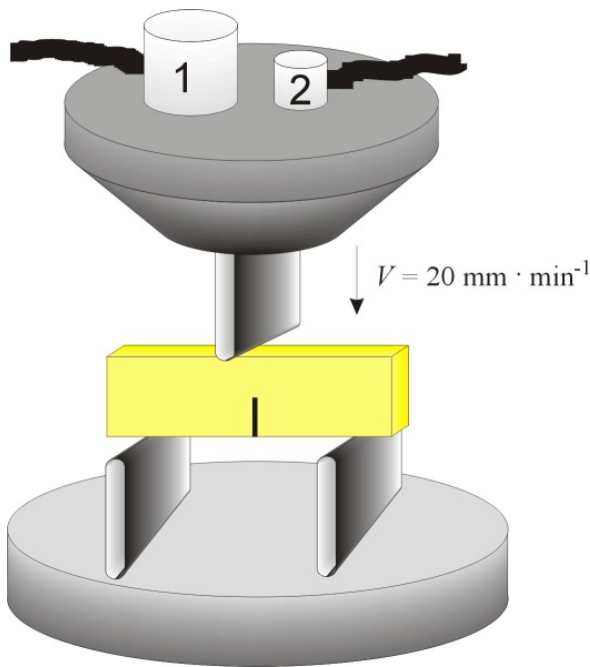


Figure 15. Scheme of the single edge notched bending SENB test for plant tissue with locations of AE sensors (1 and 2, for audible and ultrasound range for example), (by the author)

Variable	R		
	Elstar	Gloster	Jonagold
AE events	-0,77	-0,43	-0,83
Mean AE amplitude	-0,78	-0,47	-0,84
Work to maximum force	-0,52	-0,14	-0,64
K_c	-0,70	-0,18	-0,73

Table 3. Correlation coefficients R for changes work to maximum force, K_c , AE events, mean AE amplitude in SENB test and days of shelf life for three apple cultivars ‘Elstar’, ‘Gloster’ and ‘Jonagold’ (result obtained by the author)

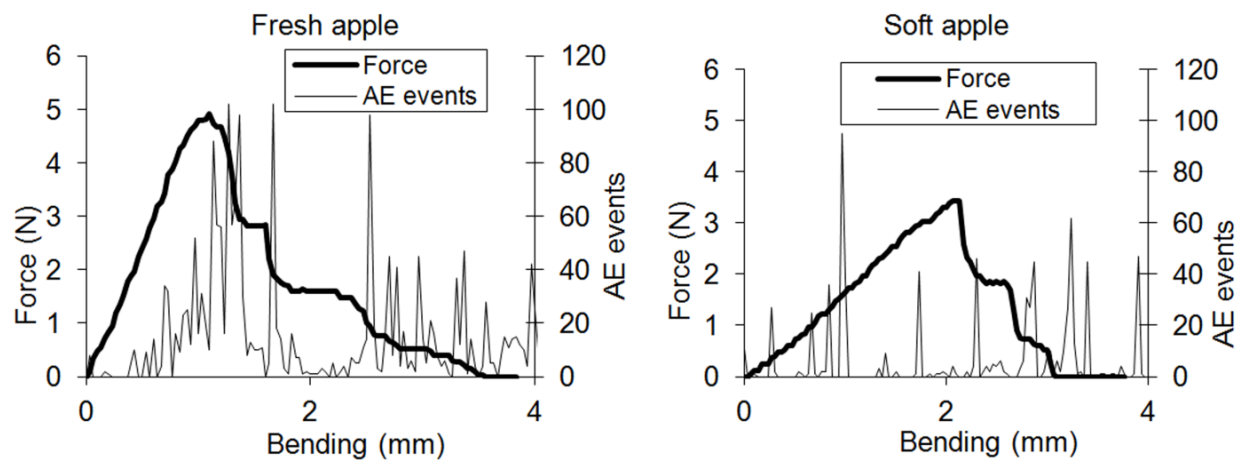


Figure 16. Typical SENB curves with acoustic emission for fresh and soft apples (result obtained by the author)

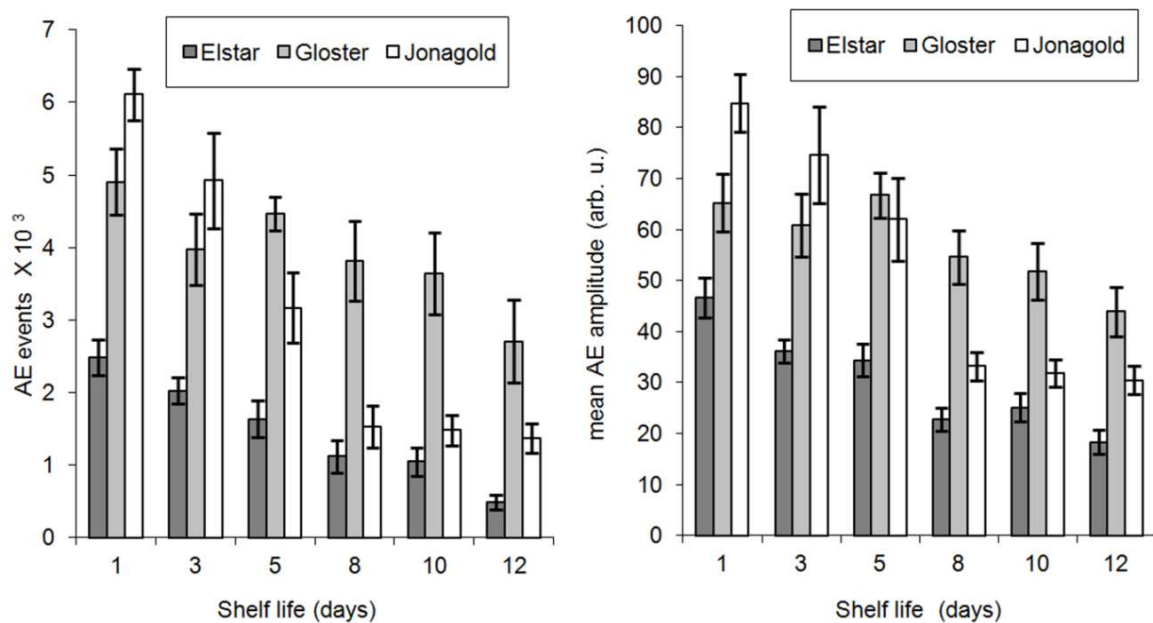


Figure 17. Change of acoustic descriptors obtained in SENB test during shelf life storage for three apple cultivars (result obtained by the author)

5. Evaluation of sensory properties with acoustic emission

There are four key factors of food quality: appearance, smell, texture, and nutritional value [11]. The first three are known as sensory acceptability factors, since they are perceived by the human senses and can be evaluated directly by the consumers. Sensory acceptability of food products is incredibly important, since people want to enjoy eating their favorite products. It can also be difficult to convince consumers to eat healthy products that are unappeal-

ing in terms of appearance and texture. Food gives us pleasure not just through its flavour or fragrance; we also want to be aware that what we are eating is fresh. In case of fruit, we associate the latter with mechanical qualities; fruits are desirable when their texture is crunchy, crisp and juicy, and less so when they are mealy.

From a mechanical perspective, crispness, juiciness, and mealiness are all associated with how the cellular structure is broken down. If biting into an apple causes the cell walls to rupture releasing intracellular juices, it makes the apple feel juicy and crispy. This is because of the acoustic signal generated as part of the process, which is perceived positively by our auditory system. It is believed also that crispness can be perceived as a combination of acoustic impressions and the strength required to break down the product, while the acoustic signal is largely perceived as vibrations by the jaw bone (bone-conducted sound). Once the cellular walls rupture, the fruit takes on a mealy quality and the fruit is generally perceived to be overripe.

Texture is a sensory characteristic; assessing it objectively is extremely difficult since consumers' personal and cultural predispositions vary greatly, and perceptions can even depend on the person's mood or frame of mind at the time. Texture of fruits and veggies is also not a constant feature, and is affected by many factors, such as natural biological variability, treatment prior to picking, time of picking, and method and duration of storage. This is why it should be monitored on an ongoing basis, while at the same time the measurements should be simple, repeatable, and low-cost. Unfortunately sensory assessment conducted by a professional panel or representative group of consumers does not meet these criteria.

Since crispness may be the bone-conducted phenomena the approach of utilizing acoustic emission with use of sensor in contact with sample is appropriate way of instrumental analysis of the sensory texture sound-related properties. An advantage of this approach is relatively low sensitivity to external noises comparing to air conducted methods, like these ones which use microphones placed close to sample. The use of the "contact" acoustic emission while mechanical test has also advantage of recording both important for consumers attributes: acoustic and mechanical ones. Typically, system used must be calibrated with reference to standard sensory analysis. Descriptors from instrumental method, independently or as a combination, should be compared with sensory texture attributes to provide the most robust calibration model as possible.

Despite of various mechanical methods used for quality testing of fruits, described previously, the puncture method is still the most popular. This simple puncture test has been used for a long time in laboratories, orchards and industry. The output of the test is firmness value expressed in Newton (N) defined as the maximum force needed to push probe into fruit flesh. In the most common configuration of the test, probe of 11.1 mm with dome-shaped ending with a radius of curvature of 8.73 mm is pushed 8 mm into the fruit. These settings are valid especially for apples. For other fruit they can be adjusted according to their hardness and dimension.

For acoustic emission, the system presented in Fig. 7 may be used. It could be a laboratory system with commercial universal testing machine (machine noise at desired speed should be considered) completed with a low noise set up for AE recording and the most important: correctly chosen sensor. Since the goal is to relate sensory perception with the instrumental method, the frequency range of sensor used can be limited to the audible range: 1-16 kHz. This range can be covered easily by one sensor only. The use of commercial devices provides possibility of easy adjusting of settings to different materials and application of different mechanical loadings programmes, however it is relatively expensive solution. Recently the first simplified system has been developed for apples only (Fig. 18). The CAED (contact acoustic emission detector developed by the author) has a fixed puncture probe and the parameter of the puncture test adjusted exactly for apple. The device uses an accelerometer with sensitivity within the audible frequency range. To avoid large data sets, electronic converts time-amplitude signal into counts in 0.1s time intervals. Counts and actual force can be exported to ASCII whereas sum of all counts (called total AE counts) in the test and firmness are displayed after each test.

A different instrument for texture evaluation was proposed by N. Sakurai's team from Japan (Fig. 19). The device uses a piezoelectric element, attached between wedge type probe for inserting into investigated material and piston driven by hydraulic mechanism [12]. Vibrations, caused by destruction by the wedge type probe of investigated fruit or veggies, are detected by piezoelement. The absolute amplitude in Volts (V) and time of duration of the signal (T) has been used for definition so called Texture Index (TI) according to the formula:

$$TI = \frac{\sum |V|}{T}. \quad (6)$$

TI could be determined within several frequency bands to check which of them could discriminate a sample. TI has been used for many fruits and vegetables as well for dry food products which showed that TI has frequency related pattern characteristic for different objects. TI was also compared with sensory texture of persimmon which showed that correlation of TI with several texture attributes (sweetness, juiciness, thickness, hardness, fragrance, appearance, and overall acceptability) can reach 0.8, particularly in the frequency range lower than 3 kHz [13].

To calibrate the instrumental method with the use of acoustic emission, a generic descriptive analysis is a suitable method for obtaining sensory texture attributes. Sensory testing laboratory should fulfil the general requirements of a standard, as an example ISO 8589:1988 standard for sensory testing conditions. Each test booth should be equipped with a system for data acquisition from panellists. The expert panel usually consists more than 6 trained persons selected on the basis of the ability of individuals to discriminate tastes and texture attributes. Before the experiment, the panellists usually take part in a training session, where definitions of attributes are discussed and clarified (as in Table 4). For the experiment pieces of fruits are assigned a code and the samples are presented to panellists in random order.

During the experiment the panellists determine the perceived intensity of texture attributes using linear, unstructured scale with a range of 0 – 100 points. After the test, the results are often converted to the most frequently used: 10-point scale.

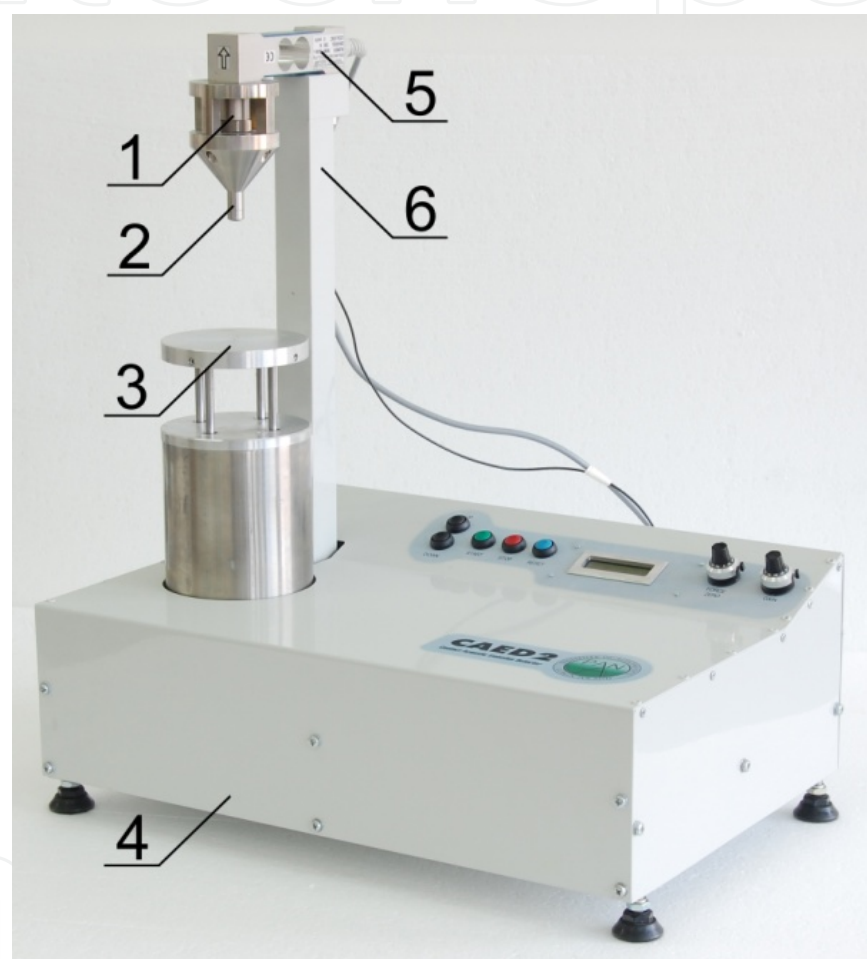


Figure 18. Contact acoustic emission detector (CAED) for apple testing developed by the author. Device uses AE sensor (1) which is placed in the AE head ended by the puncture probe (2). Apple is lift up by a motorized stage (3) to puncture probe. Force is recorded by the force sensor (5) with capacity of 200 N. Electronic (4) calculates on line AE counts and records the actual force within 0.1s time intervals. Sum of counts and firmness (N) are displayed on the screen after the test (photo by the author)

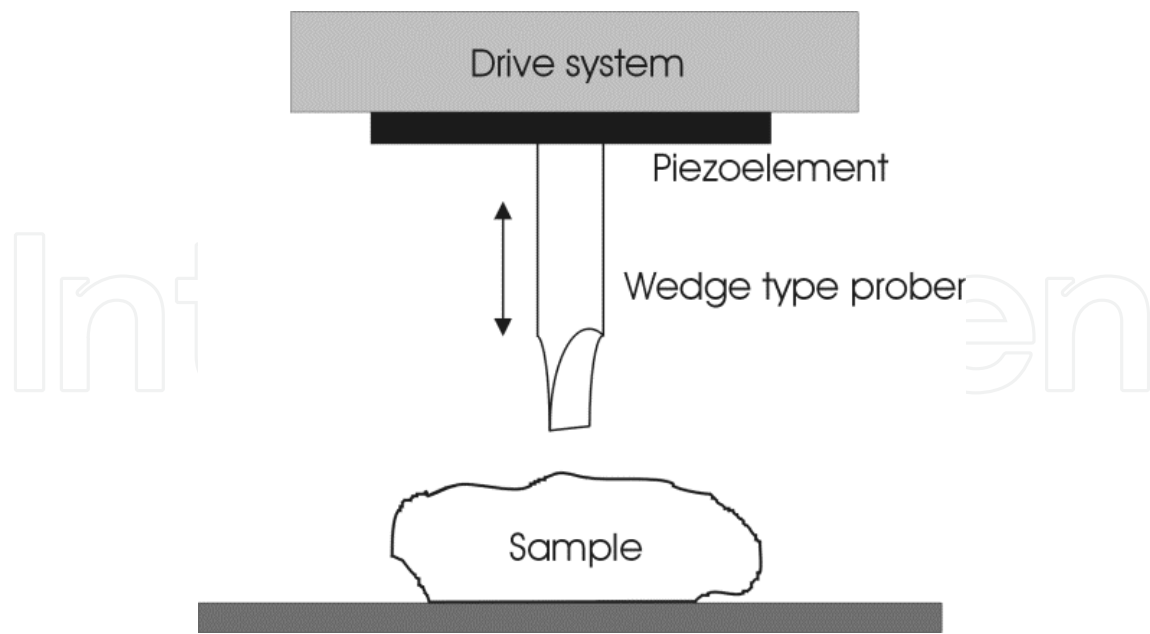


Figure 19. Scheme of device for texture index (TI) evaluation (scheme based on Taniwaki et al. [13])

Sensory texture attribute	Definition	Scale
Crispness	The sound intensity during the first bite with the front teeth	0 = no sound, 100 = very noisy
Hardness	The resistance during the first bite with the front teeth	0 = very soft, 100 = very hard
Juiciness	The sense of juice release during biting	0 = no juice, dry, 100 = very juicy
Mealiness	The mealy sense, especially on the tongue and the palate	0 = not mealy, 100 = very mealy
Overall texture	The overall sensory harmonization of textural attributes	0 = bad, 100 = very good

Table 4. Definitions and scale of some sensory texture attributes.

In the case of CAED which provides mechanical and acoustic indexes, for construction calibration models, several methods can be used: simple linear regression, multiple linear regression or multivariate regressions. For construction the models, averaged values from 10 apples (totally 244 samples from 19 apple cultivars) were taken, as it is usually assumed for sensory analysis to minimize individual preferences. Examples of statistics for different calibration models are presented in Table 5 (after Zdunek et al. [14]). These data were obtained for different 19 apple cultivars, which were stored in various ways. This example shows that the performances of the linear regression models are satisfactory for crispness and hardness prediction by both firmness or by total AE counts however quantitative pre-

diction is impossible in any case using this modelling approach. Crispness is slightly better predicted by total AE counts than by firmness when these individuals are taken for simple linear model whereas hardness is apparently better predicted by firmness than by acoustic variable. It is presumably due to different origins of the variables: sensory crispness is governed mostly from auditory phenomena whereas sensory hardness from mechanical one. Table 5 presents also performance statistics of multiple regression models (MLR) where both firmness F and total AE counts were considered in the linear model. General improvement of models is observed in the case of each sensory attribute. Furthermore, multivariate principal components regression (PCR) models, where total AE counts and firmness are used as the predictors of a group of sensory variables, show remarkable improvement of calibration performance comparing to linear regression and multiple regression models. Full cross validation (CV) in the PCR for showed that satisfactory prediction is possible in the case of hardness. The models allow for prediction also crispness and overall texture with slightly less accuracy. In the case of juiciness, successful prediction seems to be doubtful whereas mealiness prediction is impossible. Test set validation (TSV) method showed apparently better model performance in the case of crispness and slightly better in the case of juiciness whereas for the rest of sensory attributes performance from TSV method is worse than from CV method. In general both validation methods show satisfactory prediction of crispness and hardness from multivariate PCR calibration models.

The model improvement, when both acoustic and firmness are considered in calibration models, agrees with the hypothesis that crispness perception should be interpreted as counteraction of acoustic and mechanical phenomena. It is usually observed that firmer apples are also more crispy. In Fig. 8 it is visible that firmer apple has more jagged force-deformation (FD) profile during puncturing whereas soft apple has more smoother one. It was accompanied with higher AE counts at the each force dropping down. One can say that firm apple is also more brittle. The jaggedness of the FD is important from the point of view of crispness because humans can detect loads of less than 0.1 N. Such interpretation is especially true for dry food stuff however there is no reason to refuse it for plant tissue where sound is produced mainly from cell wall breakdowns and it could cause the momentary force dropping down. It has been shown for dry food that acoustic and mechanical parameters related with saw like force profile could be used for sensory crispness measurement [15], thus presumably in a future it will be the case also for fruits and vegetables.

The above calibration models for CAED were obtained with use of averaged values from 10 apples for the each calibration point. Taking into account that RMSEP value of the calibration models is slightly less than 1, an error of prediction is not larger than ± 1 . Since descriptive sensory analysis uses the 10 grade scale, the PCR calibration models allow for classification of sensory attribute to one of the 5 grades. This is very satisfactory results taking into account that the results obtained is less expensive and testing of the 10 apples lasts less than 10 minutes only. This means that instrumental evaluation of fruit texture with use of combination of sound-related descriptors and mechanical descriptors could replace soon sensory panels as it is faster, and – as is usually the case with technology – it is objective and does not suffer from fatigue.

Variables used for calibration	Validation method	Performance statistic of validation	Calibrated sensory texture attribute				
			crispness	hardness	juiciness	mealiness	overall texture
Linear regression F	CV	R ²	0.57	0.68	0.40	0.38	0.52
		RMSECV	1.10	0.86	0.95	0.83	1.05
		RPD	1.53	1.75	1.29	1.27	1.45
Linear regression C _{AE}	CV	R ²	0.62	0.60	0.48	0.33	0.52
		RMSECV	0.98	0.95	0.89	0.87	1.06
		RPD	1.72	1.63	1.45	1.27	1.50
Multi-linear regression F and C _{AE}	CV	R ²	0.71	0.77	0.53	0.43	0.62
		RMSECV	0.90	0.73	0.84	0.80	0.96
		RPD	1.87	2.07	1.46	1.32	1.59
Principal component regression F and C _{AE}	CV Ncal=244	R ²	0.72	0.77	0.53	0.43	0.63
		RMSECV	0.90	0.73	0.84	0.80	0.93
		RPD	1.87	2.12	1.53	1.38	1.71
Principal component regression F and C _{AE}	TSV Ncal=187 Ntest=57	R ²	0.90	0.77	0.67	0.25	0.51
		RMSEP	0.53	0.66	0.68	0.96	1.01
		RPD	2.91	2.04	1.61	1.15	1.44

Table 5. Performance statistics of linear regression models, multiple regression and principal component regression models for prediction sensory texture attributes of apples by CAED (after Zdunek et al [14]). Ncal – Number of samples used for calibration. Ntest – Number of samples used for validation, F-firmness, C_{AE} – total AE counts, CV-cross validation, R² – determination coefficient, RMSECV - root mean squared errors of cross validation or RMSEP - root mean squared error of prediction, RPD - ratio of prediction to deviation calculated as the ratio of standard deviation of validation data set to RMSECV or RMSEP. If the RPD was below 1.5 the model is not useful, and when the value was higher than 2, the model can predict quantitatively sensory attributes [16]

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